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Considerations Associated with the Selection of Electrochemical Protection Systems for Reinforced Concrete Structures

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ABSTRACT

Electrochemical corrosion protection systems have been used in Australia for many years for the corrosion protection of concrete infrastructure assets in marine environments.

Impressed current cathodic protection (ICCP) can be highly effective for the corrosion protection of reinforced concrete structures, however, some of the potential shortcomings of these systems are their performance in high resistivity concrete, anode installation defects in tidal zones, premature failure of some system components and the requirements for ongoing monitoring.

For galvanic-based anode systems, most of the recent innovations have been associated with backfill materials and the development of systems that incorporate a temporary impressed current phase followed by permanent galvanic protection. While the long-term performance of some of the newly developed systems is still subject to ongoing assessment, the overall performance data from galvanic-based systems indicates that one of the potential shortcomings is the inability of these systems to deliver sufficient corrosion protection over time, especially in highly corrosive environments.

This paper presents guidelines related to the selection process of the corrosion protection system for concrete structures. These guidelines have been developed based on the author's experience with the design, installation, and monitoring of various corrosion protection systems installed in Australia for the protection of marine infrastructure assets.

Key words: corrosion, cathodic protection, galvanic, anode, impressed current, ICCP, reference electrode, grout acidification, residual protection

INTRODUCTION

Impressed current cathodic protection (ICCP) for reinforced concrete structures has been installed on numerous bridges and wharves in Australia over the past 40 years. The exposure conditions at the majority of these bridges and wharves made them more susceptible to chloride-induced corrosion.

The ICCP systems in Australia are designed, installed and monitored in accordance with the global cathodic protection standards such as AMPP Standard SP 0290-2019 [1], International Standard ISO 12696:2022 [2], and Australian Standard AS 2832.5 – 2008 (R2018) [3].

While the standards include general guidelines related to ICCP installation, commissioning, monitoring and protection criteria, various aspects related to the design and installation are not addressed in the standards. The high level of interest in the cathodic protection technology in Australia among cathodic protection consultants, government authorities and assets owners has created the need for specific research work into various aspects related to the design of cathodic protection systems. Some of the recent research work on electrochemical protection applications conducted at the University of New South Wales (NSW) in Sydney, Australia included topics such as “Concrete Resistivity Impact on the Design of Impressed Current Cathodic Protection Systems” [4], “Data Analysis of the Long-Term Residual Effect of Cathodic Protection on Reinforced Concrete Structures” [5], and “Grout Acidification of Ribbon Anode in Impressed Current Cathodic Protection Systems in Concrete” [6].

Among the first ICCP systems installed in Australia were the systems for the Cockburn Cement Building and The Port Headland Ore Pier constructed in the late 1980s and early 90s. The anodes used for these structures are conductive coatings, conductive asphalt overlay and Metal Oxide (MMO) Titanium anode mesh [7].

Since the early 1990s and up until today, a large number of ICCP systems have been installed commonly using Mixed Metal Oxide (MMO) ribbon and MMO discrete anodes. These ICCP applications are typically for the protection of piles, beams and headstocks of bridges and wharves situated in marine environments. In Australia, ICCP systems are not installed on bridge decks as de-icing salt is not used on Australian roads.

Some of the prominent cathodic protection systems installed in Australia include the Sydney Opera House Western Broadwalk [8] [9], Wharves 4 & 5 of the Port of Brisbane [10], Swanson Dock and Webb Dock at the Port of Melbourne [11], the Mission and Andoom Creek Bridges in Weipa, Queensland and the cathodic prevention system installed on Seacliff Bridge in NSW [12]. For buildings, two large ICCP systems in NSW have been installed at the Trident Building in Manly, Sydney [13] and at the Monaco Building in Freshwater, Sydney.

Galvanic protection systems such as Sacrificial Anode Cathodic Protection (SACP) and Hybrid Anode Cathodic Protection (HACP) are becoming increasingly attractive because of their low monitoring costs and maintenance requirements. For several years now, galvanic anodes have been installed in conjunction with concrete patch repairs aiming to reduce the occurrence of the incipient anode effect and to prolong the life of the patch repairs. These types of galvanic systems are considered as a low-cost corrosion prevention measure. In the past 10-15 years in Australia, SACP systems and more recently, HACP systems, have been increasingly installed as global corrosion protection systems.

This paper presents a review of the overall performance of these technologies in Australia and will highlight various aspects related to improvements in the areas of design and installation of ICCP systems. Additionally, this paper includes general guidelines for selecting the optimum system for corrosion protection.

OVERVIEW OF CORROSION PROTECTION SYSTEMS

Impressed Current Cathodic Protection (ICCP)

The application of ICCP can effectively control the process of reinforcement corrosion in chloride-affected concrete structures. The technology involves the use of an external anode within the concrete to provide protection to the embedded steel reinforcement. The application of cathodic protection current promotes the development of steel passivity as a result of the production of hydroxyl ions at the steel-concrete interface which stabilize the protective passive film on the steel reinforcement. The protective oxide layer inhibits the formation of anodic and cathodic sites on the embedded steel, and this stops the corrosion reaction.

The key advantage of ICCP systems is not only their ability to control the reinforcement corrosion but to also improve the corrosion resistance of the embedded rebar. Recently published research work related to the residual effect of ICCP systems states that *"Based on the laboratory test results and analysis of data from the 6 operating CP systems, it can be generally concluded that for large percentage of the embedded rebar in a reinforced concrete structure subject to impressed current CP system, the direct result of cathodic protection is not only stopping the reinforcement corrosion but improving the corrosion resistance of the embedded rebar. The primary contributing factors for improving the corrosion resistance of embedded rebar are the reduction of chloride concentration at the steel level and the passivation of the embedded rebar as a direct result of the cathodic protection current"* [5].

Sacrificial Anode Cathodic Protection (SACP)

The use of galvanic anodes can slow the process of reinforcement corrosion in concrete applications. Galvanic anodes, normally made from zinc, are connected to embedded reinforcing steel. The difference in potential between the zinc and the steel causes a protection current to flow from the zinc to the steel.

There are various galvanic anode types designed for installation in concrete elements. Galvanic anodes are supplied with proprietary backfill which provides space for the products of anodic dissolution. Most of the recent innovations relating to galvanic anode systems have been associated with the backfill material.

While galvanic based anode systems can provide, under some specific conditions, effective corrosion protection in concrete, these systems are limited by the driving voltage of zinc in comparison to the driving voltage of ICCP systems.

The initial concept for galvanic anodes was for their use in conjunction with concrete patch repairs to reduce the occurrence of the incipient anode effect. For such applications, no permanent monitoring system is installed, and long-term assessment data is usually not available.

In the past 10-15 years in Australia, SACP systems have been installed as global corrosion protection systems mainly on small bridges. In various applications, the SACP system in the atmospheric and the tidal areas was installed in conjunction with a SACP system providing protection to the immersed elements of a bridge.

SACP technology has now been applied on multiple structures. Based on the assessment of some of these systems, the following general conclusions can be made:

- Under combined conditions of low concrete resistivity, low corrosion activity and installation of anodes at closer spacing to achieve maximum current distribution, it is possible to design SACP systems that meet (for an initial period) the cathodic protection criteria based on the applicable standards.

- The general trend for SACP systems is reduction in current delivery and corrosion protection based on the applicable protection criteria over time. Therefore, at some stage of the life of the system, the protection criteria will not be achieved, however, the level of protection may still be considered acceptable for a SACP system.

- SACP systems are significantly impacted by weather and tidal conditions. The current delivery and consequently the performance of these systems is highly affected by wet and dry weather conditions. For SACP systems installed in tidal zones, the overall performance is substantially superior to systems installed in atmospheric areas.

Under conditions of medium to high concrete resistivity and/or high corrosion activity, it is highly unlikely that a SACP system can achieve the protection criteria initially and over time regardless of the number of installed anodes. Under these conditions, for some bridges and structures, the impact of the SACP system has been negligible. Based on performance data from multiple operating SACP systems monitored by the authors, it was noted that SACP systems installed in atmospheric areas are unlikely to provide sufficient current to meet the applicable cathodic protection criteria in concrete with resistivity between 100 kΩcm and 150 kΩcm. For tidal areas, SACP systems are unlikely to meet the cathodic protection criteria with chloride content greater than 1.5 % W/W of cement and native steel potential more negative than -350mV to a Copper/Copper Sulphate reference electrode.

Hybrid Anode Cathodic Protection (HACP)

There are two types of HACP systems that have been used in Australia.

For type 1 hybrid anode systems, the sacrificial anode is used as both an impressed current and galvanic anode. Initially, a temporary power supply is used to drive a current from the installed anode to re-passivate the corroding steel. The same anode is then connected directly to the steel to provide cathodic protection by means of a galvanic current.

Type 1 hybrid anodes are made of zinc and are installed in backfill material in drilled holes in concrete. The anodes are connected by individual cables to junction boxes and to temporary power supply units. The cathodic protection current is delivered to the structure through these anodes for a pre-determined duration of time during the first stage of the process to passivate the steel. The duration of the impressed current phase is related to the resistivity of the concrete and the ability of the system to deliver the required current at the maximum permitted circuit voltage to reach the specified current requirements for this phase. Following completion of the initial impressed current phase, the temporary power supply units are removed, and the anode cables are connected to the steel for phase 2 of the galvanic protection. The system installation is similar to an ICCP installation. The main difference between ICCP installation and this type of HACP installation is that no permanent power supply unit is installed.

While in theory, HACP systems should provide better performance than SACP systems due to the passivation of steel resulted from the impressed current phase, it appears that this theoretical assumption is not applicable for type 1 HACP systems. One of the possible explanations is that the use of the same sacrificial anode as both an impressed current and galvanic anode may have a considerable impact on the ability of the anode to deliver galvanic corrosion current during stage 2.

Type 2 hybrid anode systems are based on the concept that the two-stage corrosion protection is achieved using a single anode unit encased in an activated cementitious mortar. The process allows to switch from phase 1 (impressed current phase), to phase 2 (galvanic phase) automatically.

For type 2 hybrid anode systems, a built-in battery inside the anode provides an initial phase of current to passivate the steel (phase 1). Anodes can be supplied with different battery capacities based on the system design. The system installation is simple and similar to SACP installation.

For type 2 HACP systems, the impressed current and galvanic current phases are fully independent. Stage 1 has nil negative impact on the integrity of the galvanic anode used for stage 2. Initial data of recently installed type 2 HACP systems indicates varied but generally adequate performance based on the applicable cathodic protection criteria, however, additional data would be required to verify long-term performance.

AREAS OF IMPROVEMENT OF CATHODIC PROTECTION SYSTEMS

A properly designed, installed and maintained ICCP system can provide ongoing corrosion protection for the life of the CP system in accordance with the applicable cathodic protection standards.

However, based on the assessment of a large number of concrete ICCP systems operating in Australia, there are several potential areas for improvement associated with ICCP system design:

- Consideration for concrete resistivity in the design process.
- The proper selection of locations for permanent reference electrodes for cathodic protection monitoring.
- Grout acidification and its occurrence on systems installed in tidal and splash zones.
- Various aspects related to power supply control systems.

Concrete Resistivity

The impact of concrete resistivity on the design of cathodic protection systems has been noted in all global concrete cathodic protection standards as a significant issue for consideration. However, none of the standards include specific or relevant guidelines related to the consideration of resistivity data in the design of cathodic protection systems.

Some impressed cathodic protection current systems have been designed with minimum or nil consideration of the input of concrete resistivity. The limitation of circuit voltage of ICCP systems is 8V, and in high resistivity concrete, the ability of ICCP systems to deliver sufficient current for corrosion protection can be restricted.

Recent research related to the impact of concrete resistivity on the design and performance of ICCP system concluded the following [4]:

- There is a correlation between concrete resistivity and the circuit voltage of the ICCP system. The higher the concrete resistivity, the higher the circuit voltage that is required to impress the same amount of current.

- At the same concrete resistivity value, the circuit voltage is lower at a set current output when the anode is located closer to the rebar. While the impact of anode to rebar spacing is relatively negligible at low concrete resistivity, the impact is considerable in high resistivity concrete.

- In the case of high resistivity concrete, the research found that an increase in current output can be obtained by decreasing the anode-to-rebar spacing.

- In high resistivity concrete, the location of the anode can be adjusted to achieve a lower output voltage and consequently, higher cathodic protection current. For a resistivity measurement of 1320 kΩcm, the installation of the anode relative to embedded rebar locations at 30 mm instead of 60 mm resulted in the reduction of operating circuit voltage by 183.73% from 10 volts to 3.5 volts which is well below the maximum voltage limit for CP systems operation.

The research was related to the impact of concrete resistivity with relation to impressed current cathodic protection systems. With relation to galvanic anode-based systems, the impact of high concrete resistivity is likely to be more substantial.

Reference Electrode Locations

The accurate ongoing monitoring and current adjustment of ICCP systems based on the applicable protection criteria is essential to achieve full corrosion protection.

The number and locations for reference electrodes play a central role in determining the level of cathodic protection current required to protect the embedded rebar. The entire monitoring process for ICCP systems relies on having the optimum number of reference electrodes installed in the right locations.

While this issue has been addressed in the applicable standards, greater emphasis during the installation stage should be given for the selection of reference electrode locations.

As per AS 2832.5-2008 [3], the determination of the extent and location of permanently installed performance evaluation systems (reference electrodes) shall, for each zone, take into account areas of the structure that have the following characteristics:

a) Particular sensitivity to under-protection.
b) Particular sensitivity to excessive protection.
c) High corrosion risk or activity.
d) Low corrosion risk or activity.

The reference electrodes must be placed in both high and low corrosion risk areas within the concrete element in order to eliminate the possibility of over-protection and under-protection of the embedded reinforcement. In order to select the optimum locations for installation of the reference electrodes, external potential mapping of the element must be performed.

Additionally, the location of a reference electrode must be made with consideration of the location of the anode (positive) connection, as this may impact on the sensitivity of steel potential measurement with relation to over and under-protection.

It is a requirement for a reference electrode to have a dedicated steel connection. The DC negative power return should not be used for potential measurements as the voltage flow within the CP circuit will impact on the readings recorded from the reference electrodes. Each reference electrode should be installed in a location with no direct contact between the mortar surrounding the reference electrode and the rebar.

For the protected concrete element, the size of the potential mapping area must be large enough to identify the lowest and highest corrosion activity location within the cathodic protection zone. The number of embedded reference electrodes must be sufficient in order to ensure that the entire structure protected by the ICCP system is receiving the optimum cathodic protection current.

Grout Acidification

The most common ICCP systems in Australia typically incorporate MMO ribbon anodes installed in slot cuts in the concrete cover, and/or MMO discrete anodes installed in drilled holes in the concrete.

According to SHRP- S - 372 Cathodic Protection of concrete bridges: a manual of practice [14], *"the two major anodic oxidation reactions that take place in concrete involve the evolution of either oxygen or chlorine, as follows:*

$$2H_20 = 02 + 4H^+ + 4\ e^-$$
$$2Cl^- = Cl_2 + 2\ e^-$$

In concrete, which has a relatively high pH value, the chlorine will undergo rapid hydrolysis, expressed as follows:

$$Cl_2 + H_20 = ClO^- + Cl^- + 2H^+$$

Therefore, for either anodic reaction or any combination of the two reactions, one atom of acid (H+) will be generated for the passage of each electron. Experience has demonstrated that if these reaction products are produced at a high rate because of high anode operating current densities, damage to concrete near the anode surface will result. If anode reaction products are generated slowly, they will diffuse into the concrete without causing any problems. Therefore, current density of 10 mA/ft.^{2} (108 mA/m²) on the anode surface is usually specified as a maximum".

In Australia, large sections of the ICCP systems protecting wharves and bridges are installed in tidal and splash zones and with design current densities on the anode surface not exceeding 108mA/m², however, a typical anode encapsulation detail (suitable for atmospheric exposure conditions) has been used in the tidal and splash zones.

Based on recent research on this topic [6], it was concluded that the ingress of water to the anode as a result of the anode embedment detail was the main cause of grout acidification. The elimination of water ingress to the anode can eliminate acidification problems in the tidal and splash zones.

A new encapsulation detail based on full elimination of water ingress to the anode was developed and implemented successfully over the past ten years to multiple ICCP systems with existing grout acidification problems. This detail is now incorporated in new system designs for ICCP system installations in tidal and splash zones [15].

ICCP Control Systems

For more than three decades, older generation manually operated cathodic protection systems provided the delivery of cathodic protection current to various infrastructure assets in Australia. The manually operated systems required a high level of engineering involvement for monitoring and maintenance tasks. Consequently, there was additional inherent cost for regular functional checks and carrying out the required monitoring and adjustments as per the applicable standards.

The monitoring requirements and associated costs have sometimes discouraged assets owners from selecting ICCP systems for the protection of their assets. In many cases in recent years, expensive alternative solutions with no history of performance have been selected mainly to eliminate the need for ongoing maintenance and monitoring of ICCP control systems.

The latest generation of control systems has addressed many of the concerns related to the perceived high monitoring costs related to ICCP systems. The recent developments in high precision intelligent digital power supplies, combined with the availability of industrial non-proprietary reliable components such as industrial computers and modems has allowed for the development of advanced, cost-effective and highly reliable digital ICCP control systems.

The new generation ICCP control systems offer remote functional checks and full remote testing and adjustment. These capabilities have greatly reduced the need to travel to site for functional checks and routine testing and have substantially lowered the cost of ongoing monitoring and maintenance for ICCP systems.

The concept of using solar energy to power impressed current cathodic protection systems has existed for several decades. However, the recent developments in lithium-ion battery technology, improved efficiency and the reduced cost of PV systems has led to the development of reliable Solar ICCP systems. The latest Solar ICCP systems are capable of delivering suitable cathodic protection current required for remote small and medium sized ICCP installations for reinforced concrete structures.

SELECTION OF CORROSION PROTECTION SYSTEMS

Impressed current cathodic protection (ICCP) systems are more suitable for structures with high corrosion activity due to chloride induced corrosion and when a longer design life is required for the corrosion protection system. Properly designed ICCP systems can achieve full corrosion protection regardless of the concrete resistivity.

Galvanic based anode systems can be considered for structures with low levels of chloride contamination, low concrete resistivity, low corrosion activity and shorter required design life for the protection system.

Consideration should be given to the availability of mains power supply in the vicinity of the structure. Where no mains power can be provided, Solar ICCP systems or galvanic based systems may be considered.

The selection process for the optimum system should take into consideration the structural and environmental impacts of system installation. Drilling large numbers of holes in concrete to accommodate bulky anodes may not be the most desired solution especially when alternative and less destructive options are available.

CONCLUSIONS

Electrochemical protection systems for steel in concrete can provide effective corrosion protection to structures suffering from chloride-induced corrosion. However, it is the role of engineers and consultants operating in the field of infrastructure rehabilitation to perform the required electrochemical testing and recommend the optimum solution for corrosion protection.

Various aspects of electrochemical protection systems for steel in concrete structures are detailed in the international standards and this information is available to assist owners, consulting engineers and contractors to correctly select, design, install, test, commission, monitor and maintain these systems.

With the ongoing improvements in the design of corrosion protection systems, and the technological advances in ICCP control systems, solar power technology and galvanic protection systems, asset managers can now seek out to achieve the optimum system to meet the corrosion protection requirements of their assets. The selection of a corrosion protection system must be based on a proven technology with history of performance and must be designed to achieve the protection criteria in accordance with the applicable global standards for cathodic protection.

REFERENCES

1. SP0290-2019 (formerly RP0290), Impressed Current Cathodic Protection of Reinforcing Steel in Atmospherically Exposed Concrete Structures
2. The European International Standard, Cathodic Protection of Steel in Concrete. ISO 12696:2022] (2022)
3. Standards Australia, AS 2832.5 – 2008 (R2018), Cathodic Protection of Metals, Part 5: Steel in Concrete Structures. 2018.
4. M. Cheytani, Concrete Resistivity Impact on the Design of Impressed Current Cathodic Protection Systems, PhD Thesis UNSW, Australia (2021)
5. S. Cheytani, Data analysis of the long-term residual effect of cathodic protection on reinforced concrete structures, MPhil Thesis UNSW, Australia (2020)
6. M. Cheytani, Grout Acidification of Ribbon Anode in Impressed Current Cathodic Protection Systems in Concrete MPhil Thesis UNSW, Australia (2017)
7. B.G. Ackland and R.K. Franklin, “Cathodic protection of a major Reinforced Concrete Ore Pier”, Proceedings of the First Structural Engineering Conference, Institution of Engineers Australia, Melbourne, pp 574-579, 26-28 August 1987
8. M. Tettamanti, A. Rossini; A. Cheaitani; “Cathodic Prevention and Cathodic Protection of New and Existing Concrete Elements at the Sydney Opera House”, Corrosion/97, Paper No.255, NACE, 1997
9. Atef Cheaitani, Pietro Pedeferri, Bruno Bazzoni, Philip Karajayli, Ray Dick, Performance of Cathodic Prevention System of Sydney Opera House Underbroadwalk after 10 Years of Operation, Paper No. 06342, NACE 2006
10. Atef Cheaitani, “Cathodic Protection to the Port of Brisbane Structure, Australia, paper no 545, NACE , Corrosion 99
11. Atef Cheaitani, Paul Daffy, Durability Strategy in Relation to Service Life for Structures in Marine Environments, Coasts & Port 2007, Melbourne, Victoria
12. Cheaitani, A, Karajayli, P, Chun-Ni, J “Application of Cathodic Prevention to Sea Cliff Bridge, Lawrence Hargrave Drive”. Corrosion & Prevention 2006, Paper 006.

13. Atef Cheaitani, Brian Close, Cathodic Protection of a Multi-Story Building, method of project delivery and long-term maintenance, ACA Conference 2007, Darling Harbour, Sydney
14. Bennett J et al, Cathodic Protection of Concrete Bridges: A Manual of Practice, SHRP –S-372 (1993), page 28.
15. Cheaitani Atef, Cheytani Samir. Future directions for designing low maintenance impressed current cathodic protection systems. EuroCorr 2018 conference & exhibition. Cracow, Poland